DARK MATTER AND STERILE NEUTRINOS

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Dark matter has been recognized as an essential part of matter for over 70 years now, and many suggestions have been made, what it could be. Most of these ideas have centered on Cold Dark Matter, particles that are predicted in extensions of standard particle physics, such as supersymmetry. Here we explore the concept that dark matter is sterile neutrinos, particles that are commonly referred to as Warm Dark Matter. Such particles have keV masses, and decay over a very long time, much longer than the Hubble time. In their decay they produce X-ray photons which modify the ionization balance in the very early universe, increasing the fraction of molecular Hydrogen, and thus help early star formation. Sterile neutrinos may also help to understand the baryon-asymmetry, the pulsar kicks, the early growth of black holes, the minimum mass of dwarf spheroidal galaxies, as well as the shape and smoothness of dark matter halos. As soon as all these tests have been made quantitative in their various parameters, we may focus on the creation mechanism of these particles, and could predict the strength of the sharp X-ray emission line, expected from any large dark matter assembly. A measurement of this X-ray emission line would be definitive proof for the existence of may be called weakly interacting neutrinos, or WINs.

Keywords: Dark matter, sterile neutrinos, galaxies, black hole physics

1. Introduction

Since the pioneering works of Oort[1] and Zwicky,[2,3] it has been known that there is dark matter in the universe, matter that interacts gravitationally, but not measurably in any other way. Oort argued about the motion and density of stars perpendicular to the Galactic plane, and in this case, Oort's original hunch proved to be correct, the missing matter turned out to be low luminosity stars. Zwicky argued about the motions and densities of galaxies in clusters of galaxies, and to this day clusters of galaxies are prime arguments to determine dark matter, and its properties.[4,5]

Based on the microwave back ground fluctuations[6] today we know that the universe is flat geometrically, i.e. the sum of the angles in a cosmic triangle is always 180 degrees, provided we do not pass too close to a black hole. This finding can be translated into stating that the sum of the mass and energy contributions to the critical density of the universe add up to unity, with about 0.04 in baryonic matter, about 0.20 in dark matter, and the rest in dark energy; we note that there is no consensus even where to find all the baryonic matter, but a good guess is warm to hot gas, such as found in groups and clusters of galaxies, and around early Hubble type galaxies.[7,8]

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There are many speculations of what dark matter is; we have three constraints:

1) It interacts almost exclusively by gravitation, and not measurably in any other way. 2) It does not participate in the nuclear reactions in the early universe. 3) It must be able to clump, to help form galaxies, and later clusters of galaxies, and the large scale structure.[9] Other options, such as particles in higher dimensions, also exist,[10] and other gravitational theories.[11–15] Obviously, various extensions in particle physics theory, such as supersymmetry, provide candidates like the lightest supersymmetric particle.

Here we focus on the concept that it may be a "sterile neutrino", a right-handed neutrino, that interacts only weakly with other neutrinos, and otherwise only gravitationally. Such particles were proposed first by Pontecorvo[16] and later by Olive & Turner.[17] Sterile neutrinos were further proposed as as dark matter candidates.[18] It was then shown how oscillations of normal neutrinos to sterile neutrinos could help explain the very large rectilinear velocities of some pulsars.[19]

Observationally the evidence comes from a variety of arguments: i) Dark matter in a halo like distribution is required to explain the stability of spiral galaxy disks;[20–22] ii) the flat rotation curves of galaxies;[23] and iii) the containment of hot gas in early Hubble type galaxies.[24] Dark matter is also required to explain: iv) the structure of clusters of galaxies;[25,26] v) the structure formation[27] and the flat geometry of the universe.[6,28] We refer the reader to a recent review[9] and a book[29] on dark matter.

Therefore after more than 70 years we still face the question: "What is dark matter?"

2. The dark matter session at Berlin

A much wider range of topics was explored in the session, than what we can survey in extenso; we will confine ourselves to the limited topic at hand subsequently.

- Shaposhnikov, Mikhail: Sterile neutrino dark matter.
  His lecture is also contained among the reports. He reviewed the basic particle physics ingredients and some of his latest work is summarized in various papers.[30–35]
- Mapelli, Michela: Impact of dark matter decays and annihilations on reionization
  We consider four different dark matter candidates (light dark matter, gravitinos, neutralinos and sterile neutrinos), for each of them deriving the decaying/annihilation rate, the influence on reionization, matter temperature and structure formation. We find that light dark matter particles (1 - 10 MeV) and sterile neutrinos (2 - 8 keV) can be sources of partial early reionization ($z < 100$). However, their integrated contribution to Thomson optical depth is small (< 0.01) with respect to the three year WMAP results. Finally, they can significantly affect the behavior of matter temperature, delaying the formation of first stars. On the contrary, effects of

heavy dark matter candidates (gravitinos and neutralinos) on reionization and heating are minimal.[36,37]

- Ripamonti, Emanuele: Dark matter decay and annihilation influence upon structure formation
  DM decays and annihilations might heat and ionize the primordial IGM, affecting its thermal and chemical evolution. We investigate whether they can also change the "critical mass" which is needed for a primordial halo to cool and form stars. This is done through a 1-D hydrodynamical code, where we included the treatment of the chemical evolution of the gas, and of the effects of different models of DM decays/annihilations. The results are mixed: in some cases (e.g. sterile neutrinos) the critical mass remains almost unchanged; in other cases (e.g. light dark matter decays) it increases significantly. In fact, the enhanced ionized fraction catalyzes H_2 formation and favours cooling, but this is not sufficient to compensate for the effects (e.g. the increase in the Jeans mass) of the extra heating.[38]
- Stasielak, Jaroslaw: Evolution of the primordial clouds in the warm dark matter model with keV sterile neutrinos
  We analyze the processes relevant for star formation in a model with dark matter in the form of sterile neutrinos. Sterile neutrino decays produce an X-ray background radiation that has a two-fold effect on the collapsing clouds of hydrogen. First, the X-rays ionize gas and cause an increase in the fraction of molecular hydrogen, which makes it easier for the gas to cool and form stars. Second, the same X-rays deposit a certain amount of heat, which could, in principle, thwart the cooling of gas. We find that, in all the cases we have examined, the overall effect of sterile dark matter is to facilitate the cooling of gas. Hence, we conclude that dark matter in the form of sterile neutrinos can facilitate the early collapse of gas clouds and the subsequent star formation.[39]
- Slosar, Anze: Cosmological constraints on sterile neutrinos
  Sterile neutrinos come in two kinds in the cosmological context. On one hand we have very weakly coupled sterile neutrinos with masses of the order of a few keV that act as a dark matter candidate. On the other hand people are also considering light and completely thermalized neutrino species with masses of around 1 eV or less. I will discuss how cosmology can constrain both of these sterile neutrino candidates, what are the present limits and possible work-arounds.[40,41]
- Guzman, Murillo Francisco Siddhartha: Scalar field dark matter: beyond the spherical collapse
  We show the evolution of non-spherically symmetric balls of a self-gravitating scalar field in the Newtonian regime or equivalently an ideal self-gravitating condensed Bose gas. In order to do so, we use a finite difference approximation of the Schrödinger-Poisson (SP) system of equations with axial symmetry in cylindrical coordinates. Our results indicate: 1)

that spherically symmetric equilibrium configurations are stable against non-spherical perturbations and 2) that such equilibrium configurations of the SP system are late-time attractors for non-spherically symmetric initial profiles of the scalar field, which is a generalization of such behavior for spherically symmetric initial profiles. Our system and the boundary conditions used, work as a model of scalar field dark matter collapse after the turnaround point. In such case, we have found that the scalar field overdensities tolerate non-spherical contributions to the profile of the initial fluctuation.[42,43]

- Khriplovich, Iosif: Upper limits on density of dark matter in Solar system
  The analysis of the observational data for the secular perihelion precession of Mercury, Earth, and Mars, based on the EPM2004 ephemerides, results in new upper limits on density of dark matter in the Solar system.[44]
- Popa, Lucia and Vasile, Ana: Sterile Neutrino as Dark Matter candidate from CMB alone
  Distortions of CMB temperature and polarization maps caused by gravitational lensing, observable with high angular resolution and sensitivity, can be used to constrain the sterile neutrino mass, m_s, from CMB data alone. We forecast $m_s > 1.75$ keV from Planck and $m_s > 4.97$ keV from Inflation Probe at 95% CL, by using the CMB weak lensing extraction.[45]
- Kronberg, Philip P.: Interconnections between black holes, magnetic fields, cosmic rays in the Universe: A Review
  I review the interconnections among these, focusing on consequences of energy efficiency and the magnetic field generation by massive black holes. The remarkable conversion efficiency from gravitational to magnetic energy is discussed. Although it is ill-understood, recent global tests already serve to constrain magnetic field creation scenarios.
  Energy flows and magnetic fields arising from galactic black holes are discussed, and also the close connections to cosmic ray acceleration issues. New radio detections of diffuse extragalactic radio emission on degree-scales will be described, and also the first attempts to probe the level of magnetic fields in cosmological large scale structure directly by Faraday rotation. These are compared with theoretical predictions of diffuse magnetic field strengths.[46]
- Gergely, Laszlo: Is dark matter futile on the brane?
  Rather than introducing various type of candidates for dark matter, gravitational dynamics can be modified in order to explain the observations. One route to do this is in the framework of the so-called brane-world theories,[47,48] in which our observable universe is a brane embedded into a higher dimensional space-time (the bulk). In these theories the apparent gravitational dynamics on our observable 4-dimensional universe is given by the twice contracted Gauss equation, the Codazzi equation and the effective Einstein equation.[49]
  Gergely has discussed whether dark matter can be replaced by vari-

ous source terms appearing in the effective Einstein equation. Such non-conventional source terms include a quadratic (ordinary) matter source term, a geometric source term originating in the Weyl curvature of the bulk, a source term arising from the possible asymmetric embedding, and finally the pull-back to the brane of possible non-standard model bulk fields. The non-linear source term modifies only the very early cosmology,[50] due to the enormous value of the brane tension.

The Weyl curvature of the bulk in a spherically symmetric brane-world metric generates a dark matter mass.[51] With no cosmological constant, the dark mass scales linearly with the radial distance, explaining the flatness of the galactic rotation curves.

Properly chosen non-standard model bulk fields can replace dark matter in explaining structure formation,[52] the evolution of perturbations on the brane becoming similar to that of the Cold Dark Matter (CDM) model.

With a radiating black hole only on one side of the brane, interesting phenomena occur. The combined effect of asymmetry and a bulk radiation qualitatively gives both dark matter and dark energy.[53,54] The radiation pressure accelerates the brane, as would dark energy do, while the absorbed radiation increases the energy density of the bulk, appearing as CDM. These two effects compete with each other, and with properly chosen initial data a critical-like behavior can be found.

- Watson, Casey: Direct X-ray Constraints on Sterile Neutrino Warm Dark Matter

  In this talk, I will discuss how we use the diffuse X-ray spectrum (total minus resolved point source emission) of the Andromeda galaxy to constrain the rate of sterile neutrino radiative decay and the sterile neutrino mass, m_s. Our findings demand that $m_s < 3.5$ keV (95% C.L.) which is a significant improvement over the previous (95% C.L.) limits inferred from the X-ray emission of nearby clusters, $m_s < 8.2$ keV (Virgo A) and $m_s < 6.3$ keV (Virgo A + Coma).[55]
- Riemer-Sørensen, Signe: Probing the nature of dark matter with Cosmic X-rays

  Gravitational lensing observations of galaxy clusters have identified dark matter "blobs" with remarkably low baryonic content. We use such a system to probe the particle nature of dark matter with X-ray observations. We also study high resolution X-ray grating spectra of a cluster of galaxies. From these grating spectra we improve the conservative constraints on a particular dark matter candidate, the sterile neutrino, by more than one order of magnitude. Based on these conservative constraints obtained from cosmic X-ray observations alone, the low mass ($m_s < 10$ keV) and low mixing angle ($\sin^2(2\theta) < 10^{-6}$) sterile neutrino is still a viable dark matter candidate.[56,57] In Fig. 1, the lifetime of the sterile neutrino is plotted as a function of the photon energy E in keV.

- Munyaneza, Faustin: Limits on the dark matter particle mass from black hole growth in galaxies
  I review the properties of degenerate fermion balls and investigate the dark matter distribution at galactic centers using NFW, Moore and isothermal density profiles. I show that dark matter becomes degenerate for particles masses of a few keV and for distances less than a few parsec from the center of our galaxy. To explain the galactic center black hole of mass of $\sim 3.5 \times 10^6 M_\odot$ and a supermassive black hole of $\sim 3 \times 10^9 M_\odot$ at a redshift of 6.41 in SDSS quasars,[58] we require a fermion ball mass between $3 \times 10^3 M_\odot$ and $3.5 \times 10^6 M_\odot$. This leads to strong limits on the mass of the dark matter particle between 0.64 keV and 5.82 keV for NFW profile, and between 0.97 keV and 13.81 keV for Moore profile and finally the dark matter mass is found to be constrained between 2.38 keV and 81.65 keV for the isothermal gas sphere case. I then argue that the constrained particle could be the long sought dark matter of the Universe that is interpreted as a sterile neutrino.[59–61] The limits on the sterile neutrino mass are shown in Fig. 2.
- Ruchayskiy, Oleg: Search for the light dark matter with an X-ray spectrometer
  Sterile neutrinos with the mass in the keV range are interesting warm dark matter (WDM) candidates. The restrictions on their parameters (mass and mixing angle) obtained by current X-ray missions (XMM-Newton or Chandra) can only be improved by less than an order of magnitude in the near future. Therefore the new strategy of search is needed. We compare the sensitivities of existing and planned X-ray missions for the detection of WDM particles with the mass 1 - 20 keV. We show that existing technology allows an improvement in sensitivity by a factor of 100. Namely, two different designs can achieve such an improvement: [A] a spectrometer with the high spectral resolving power of 0.1 %, wide (steradian) field of view, with small effective area of about cm^2 (which can be achieved without focusing optics) or [B] the same type of spectrometer with a smaller (degree) field of view but with a much larger effective area of $10^3 cm^2$ (achieved with the help of focusing optics). To illustrate the use of the "type A" design we present the bounds on parameters of the sterile neutrino obtained from analysis of the data taken by an X-ray microcalorimeter. In spite of the very short exposure time (100 sec) the derived bound is comparable to the one found from long XMM-Newton observation.[62]
- Gilmore, Gerard: Dwarf spheroidal galaxies
  The Milky Way satellite dwarf spheroidal (dSph) galaxies are the smallest dark matter dominated systems in the universe. We have underway dynamical studies of the dSph to quantify the shortest scale lengths on which Dark Matter is distributed, the range of Dark Matter central densities, and the density profile(s) of DM on small scales. Current results suggest some

surprises: the central DM density profile is typically cored, not cusped, with scale sizes never less than a few hundred pc; the central densities are typically 10-20 GeV/cc; no galaxy is found with a dark mass halo less massive than $5\ 10^7\ M_\odot$. We are discovering many more dSphs, which we are analysing to test the generality of these results.[63] In Fig. 3, the inferred dark mass is shown for different dwarf spheroidal galaxies.

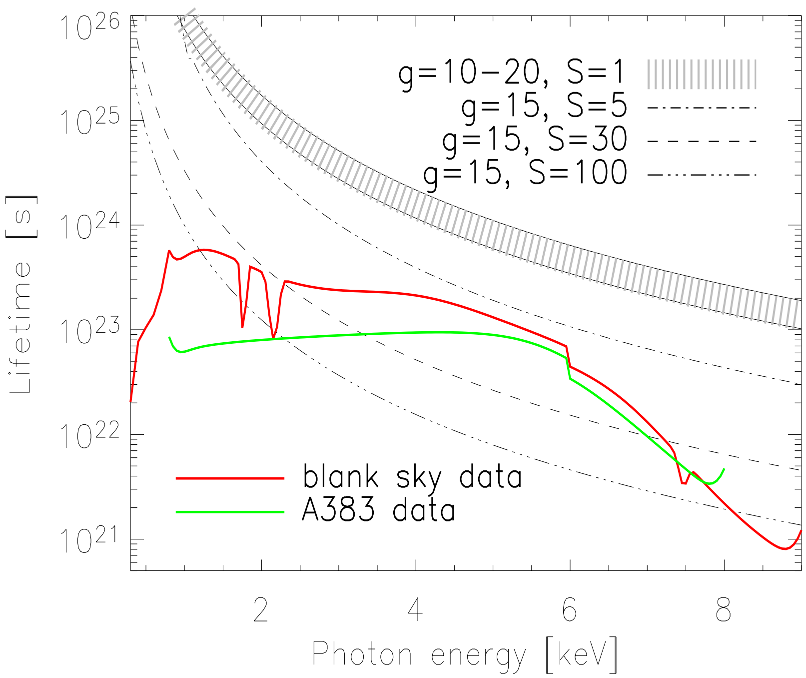

Fig. 1. The lifetime constrained from the flux of the Chandra blank sky data (red) and A383 (green). The νMSM prediction for $S = 1$ and $g_* = 10 - 20$ (hatched) and several variations of S and g_* (black) have been overplotted. This plot has been adapted from ref.[56] under the permission of the authors. Full explanation of the parameters S and g_* are found in the same reference.

3. Proposal

The existing proposals to explain dark matter mostly focus on very massive particles,[9] such as the lightest supersymmetric particle; all the experimental searches are sensitive for masses above GeV, usually far above such an energy. In the normal approach to structure formation, this implies a spectrum of dark matter clumps extending far down to globular cluster masses and below. It has been a difficulty for some time that there is no evidence for a large number of such entities near

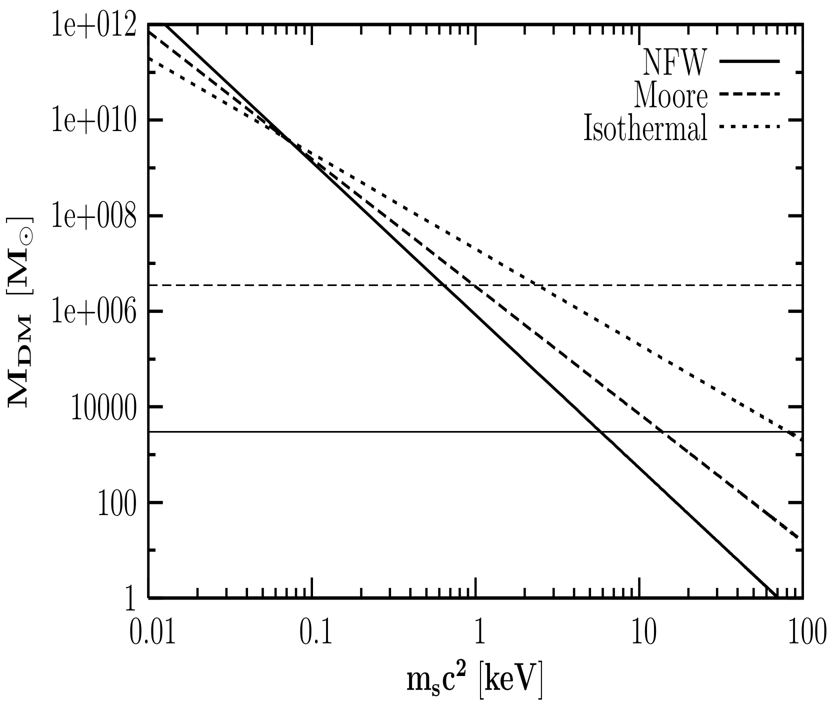

Fig. 2. The total mass M_{DM} of the fermion ball as a function of the fermion mass m_s. The total mass M_{DM} scales with the the DM particle mass m_s as $m_s^{-16/5}$, $m_s^{-8/3}$ and as m_s^{-2} for NFW, Moore and isothermal power law, respectively. Two horizontal lines at $M_{DM} = 3.5 \times 10^6 M_\odot$ and $M_{DM} = 3 \times 10^3 M_\odot$ have been drawn to get the lower and upper limits on the mass of the DM particle. From this plot, a sterile neutrino mass could be in the range from 1 keV to about 80 keV. The lower limit could be improved to about 7 keV if the Fermi Dirac distribution is used in solving the Poisson's equation for the gravitational pontential of sterile neutrinos.[59,61] This graph has been taken from ref.[60]

our Galaxy. The halo is clumpy in stars, but not so extremely clumpy. If, however, the mass of the dark matter particle were in the keV range, then the lowest mass clumps would be large enough to explain this lack. However, in this case the first star formation would be so extremely delayed[64] that there would be no explanation of the early reionization of the universe, between redshifts 11 and 6, as we now know for sure.[6,28] Therefore, the conundrum remained.

Here we explore the concept that the dark matter is indeed of a mass in the keV range, but can decay, and so produce in its decay a photon, which ionizes. It so increases the abundance of molecular Hydrogen, and so allows star formation to proceed early.[39,65] The specific model we explore is of "sterile neutrinos", right handed neutrinos, which interact only with normal, left-handed neutrinos, and with gravity. Such particles are commonly referred to as "Warm Dark Matter", as opposed to "Cold Dark Matter", those very massive particles. For most aspects of

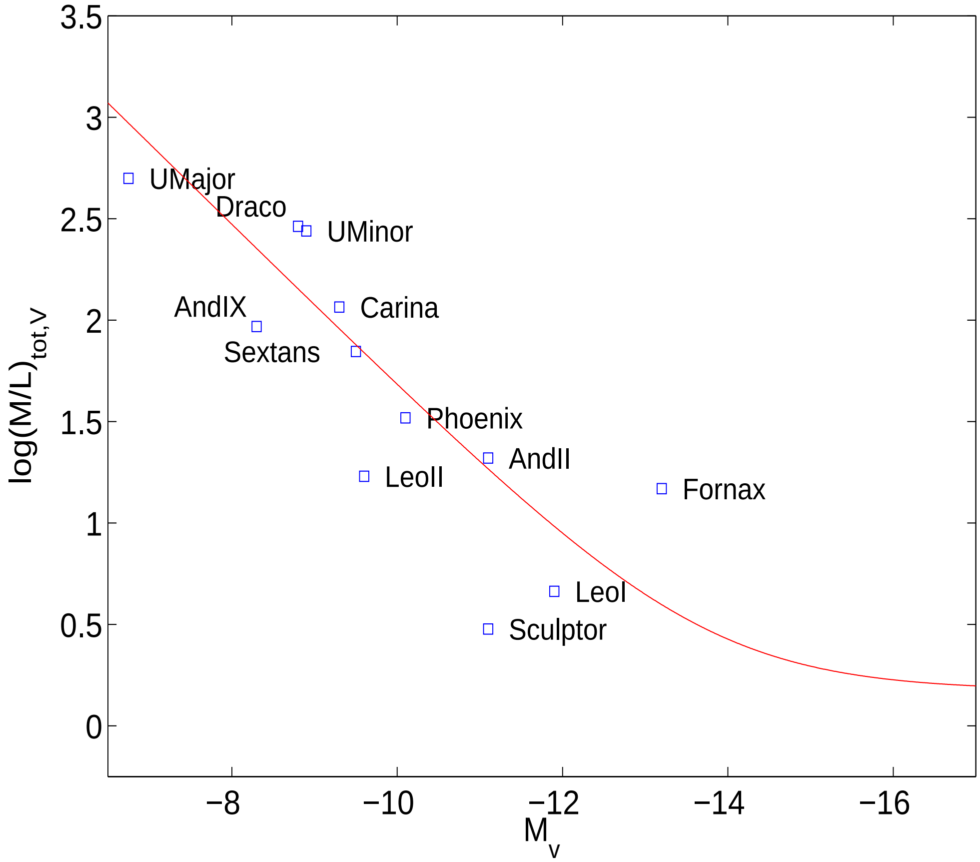

Fig. 3. Mass to light ration vs galaxy absolute V magnitude for some Local Group dSphs galaxies. The solid curve shows the relation expected if all the dSphs galaxies contain about $4 \times 10^7 M_\odot$ solar masses of dark matter interior to their stellar distributions. This plot has been adapted from ref.[63] under the permission of the author.

cosmology warm dark matter and cold dark matter predict the same; only at the small scales are they significantly different, and of course in their decay.

The mass range we explore is approximately 2 - 25 keV. These sterile neutrinos decay, with a very long lifetime, and in a first channel give three normal neutrinos, and in the second channel, a two-body decay, give a photon and a normal neutrino. The energy of this photon is almost exactly half the mass of the initial sterile neutrino.

What is important is to understand that such particles are not produced from any process in thermal equilibrium, and so their initial phase space distribution is far from thermal; current models for their distribution suggest that their momenta are sub-thermal. The measure of how much they are subthermal modifies the precise relationship between the dark matter particle mass and the minimum clump mass, which should be visible in the smallest pristine galaxies.

This also entails, that as Fermions they require a Fermi-Dirac distribution, as being far from equilibrium, this distribution implies a chemical potential.[59]

Recent work by many others[30–35,66–74] has shown that these sterile neutrinos can be produced in the right amount to explain dark matter, could explain the baryon asymmetry,[75] explain the lack of power on small scales (as noted above), and could explain the dark matter distribution in galaxies.[63,76,77]

3.1. *Our recent work*

Pulsars are observed to reach linear space velocities of up to over 1000 km/s, and there are not many options how to explain this; one possibility is to do this through magnetic fields which become important in the explosion;[78–82] curiously, normal neutrinos played a role already in these early ideas. Another possibility is to do this through a conversion of active neutrinos which scatter with a mean free path inside the exploding massive star of about ten cm,[83] into sterile neutrinos, which no longer scatter. If this conversion produces a spatial and directional correlation between the sterile neutrinos and the structure of the highly magnetic and rotating core of the exploding star, then a small part of the momentum of the neutrinos can give an asymmetric momentum to the budding neutron star, ejecting it at a high velocity.[84] This then could explain such features as the guitar nebula,[85] the bow shock around a high velocity pulsar. This latter model in one approximation requires a sterile neutrino in the mass range 2 to 20 keV. It is remarkable that this neutrino model requires magnetic fields in the upper range of the strengths predicted by the magneto-rotational mechanism to explode massive stars as supernovae.

It was shown from SDSS data,[58,86] that some quasars have supermassive black holes already at redshift 6.41, i.e. at about 800 million years after the big bang. We now know, that this is the period when galaxies grow the fastest, from 500 to 900 million years after the big bang.[87,88] Baryonic accretion has trouble feeding a normal black hole to this high mass, $3\ 10^9$ solar masses so early after the big bang, if the growth were to start with stellar mass black holes.[89] So either the first black holes are around 10^4 to 10^6 solar masses, and there is not much evidence for this, or the early black holes grow from dark matter,[59–61] until they reach the critical minimum mass to be able to grow very fast and further from baryonic matter, which implies a mass range of about 10^4 to 10^6 solar masses. This model in the isothermal approximation for galaxy structure implies a sterile neutrino in the mass range between 12 and 450 keV.

When Biermann and Kusenko met at an Aspen meeting September 2005, it became apparent, that these two speculative but very different approaches overlap, and so it seemed worth to pursue them further.

As noted above, structure formation arguments lead to an overprediction in power at small scales in the dark matter distribution in the case of cold dark matter, and any attempt to solve this with warm dark matter delayed star formation unacceptably.[64] We convinced ourselves that this was the key problem in reconciling warm dark matter (keV particles) with the requirements of large scale structure and reionization. We then showed that the decay of the sterile neutrino could increase the ionization, sufficiently to enhance the formation of molecular hydrogen, which in turn can provide catastrophic cooling early enough to allow star formation as early as required.[39,65] In our first simple calculation this happens at redshift 80. More refined calculations confirm, that the decay of sterile neutrinos helps increase the fraction of molecular Hydrogen, and so help star formation, as long as this is at redshifts larger than about 20.[36–38]

4. The tests

4.1. *Primordial magnetic fields*

In the decay a photon is produced, and this photon ionizes Hydrogen: at the first ionization an energetic electron is produced, which then ionizes much further, enhancing the rate of ionization by a factor of about 100. In the case, however, that there are primordial magnetic fields, this energetic electron could be caught up in wave-particle interaction, and gain energy rather than lose energy. As the cross section for ionization decreases with energy, the entire additional ionization by a factor of order 100 would be lost in this case, and so there basically would be no measurable effect from the dark matter decay. This gives a limit for the strength of the primordial magnetic field, given various models for the irregularity spectrum of the field: In all reasonable models this limit is of order a few to a few tens of picoGauss, recalibrated to today.

Recent simulations matched to the magnetic field data of clusters and superclusters, give even more stringent limits, of picoGauss or less.[90]

It follows that primordial magnetic fields can not disturb the early ionization from the energetic photons, as a result of dark matter decay. It then also follows that the contribution of early magnetic fields from magnetic monopoles, or any other primordial mechanism, is correspondingly weak.[91]

Stars at all masses are clearly able to produce magnetic fields,[92–94] but the evolution and consequent dispersal are fastest for the massive stars, almost certainly the first stars. As the magnetic fields may help to drive the wind of these massive stars,[95] then the wind is just weakly super-Alfvénic, with Alfvénic Machnumbers of order a few. This implies that the massive stars and their winds already before the final supernova explosion may provide a magnetic field which is at order 10 percent equipartition of the environment; this magnetic field is highly structured. However, even these highly structured magnetic fields will also allow the first cosmic rays to be produced, and distributed, again with about 10 percent of equipartition of the environment. The question on how magnetic fields arising from galaxies can get distributed across the cosmos has been investigated in by various authors.[46,96–98] However, the large scale structure and coherence of the cosmic magnetic fields clearly remain an unsolved problem.[99–101]

Therefore the first massive stars are critical for the early evolution of the universe: In addition to reionization, magnetic fields and cosmic rays, these stars provide the first heavy elements. These heavy elements allow in turn dust formation, which can be quite rapid (as seen, e.g., in SN 1987A, already just years after the explosion[102]). This then enhances the cooling in the dusty regions, allowing the next generation of stars to form much faster.

In combination everywhere one first massive star is formed, we can envisage a runaway in further star formation in its environment.

4.2. *Galaxies*

Galaxies merge, and simulations demonstrate that the inner dark matter distribution attains a power law in density, and a corresponding power law tail in the momentum distribution:[103–105] Here the central density distribution as a result of the merger is a divergent power law, as a result of energy flowing outwards and mass flowing inwards, rather akin to accretion disks,[106–111] where angular momentum flows outwards and mass also flows inwards; in fact also in galaxy mergers angular momentum needs to be redistributed outwards as such mergers are almost never central.[112] This then leads to a local escape velocity converging with r to zero, and so for fermions the Pauli limit is reached, giving rise to a cap in density, and hence give birth to a dark matter star, also called a fermion ball.[59,60] this dark matter star can grow further by dark matter accretion. The physics of fermion balls as a model for the dark matter distribution at galactic centers has been studied in a series of papers.[113–119] For realistic models an integral over a temperature distribution is required, and a boundary condition has to be used to represent the surface of the dark matter star both in real space as in momentum space. This then allows the mass of this dark matter star to increase further. In quantum statistics, such models resemble white dwarf stars or neutron stars as the Pauli's pressure upholds the star. As seen in Fig. 2, for fermions in the keV range, the mass of the dark matter star has a mass range of a few thousand to a few million solar masses.

The first stellar black hole can then enter this configuration and eat the dark matter star from inside, taking particles from the low angular momentum phase space. With phase space continuously being refilled through the turmoil of the galaxy merger in its abating stages, or in the next merger, the eating of the dark matter star from inside ends only when all the dark matter star has been eaten up.

Given a good description of the dark matter star boundary conditions in real and in momentum phase space,[59,60] and an observation of the stellar velocity dispersion close to the final black hole, but outside its immediate radial range of influence, we should be able to determine a limit to the dark matter particle mass. If the entire black hole in the Galactic Center has grown from dark matter alone, then we obtain a real number of about 6 to 10 keV.[59,61]

This concept suggests that it might be worthwhile to consider the smallest of all black holes in galactic centers. In a plot of black hole mass M_{BH} versus central stellar velocity dispersion σ there is a clump above the relation $M_{BH} \sim \sigma^4$ at low black hole masses,[120,121] suggesting that perhaps we reach a limiting relationship with a flatter slope for all those black holes which grow only from dark matter. For an simple isothermal approach this flatter slope is 3/2 as obtained in ref.[60]

4.3. *Dwarf spheroidal galaxies*

All detected dwarf spheroidal galaxies fit a simple limiting relationship of a common dark matter mass of $4\,10^7$ solar masses,[63] suggesting that this is perhaps the smallest dark matter clump mass in the initial cosmological dark matter clump spectrum. This clump mass is of course a lower limit to the true original mass of the pristine dwarf spheroidal galaxy. Fig. 3 shows the distribution of dark matter mass for various dwarf spheroid galaxies. Given a physical concept for the production of the dark matter particles in the early universe, we would have their initial momentum, probably subthermal, and so the connection between the dark matter particle mass and minimum clump mass is modified. This is a very strong support for the Warm Dark Matter concept and the associated problems have been pointed out in a number of papers.[122–124]

One intriguing aspect of dwarf spheroidal galaxies is that almost all of them show the effect of tidal distortion in their outer regions, and at least one of them has been distended to two, perhaps even three circumferential rings around our Galaxy.[76,77] To extend so far around our Galaxy must have taken many orbits, and so some fraction of the age of our Galaxy. The simple observation that these streamers still exist separately, and can be distinguished in the sky, after many rotations around our Galaxy, implies that the dark matter halo is extremely smooth, and also nearly spherically symmetric. Given hat the stellar halo is quite clumpy this implies once more that the dark matter is much more massive than the baryonic matter in our halo. Metallicities and detailed spectroscopy give a throve of further information.[125,126] Small spiral galaxies may or may not be different.[127]

4.4. *Lyman alpha forest*

In the early structure formation the large number of linear perturbations in density do not lead to galaxies, but just to small enhancements of Hydrogen density, visible in absorption against a background quasar. This so-called Lyman alpha forest tests the section of the perturbation scales which is linear and so much easier to understand, and it should in principle allow a test for the smallest clumps.[128,129] Unfortunately, systematics make this test still difficult, and with the expected subthermal phase space distribution of the dark matter particles, we may lack yet the sensitivity to determine the mass of the smallest clumps.

4.5. *The X-ray test*

When the sterile neutrinos decay, they give off a photon with almost exactly half their mass in energy. Our nearby dwarf spheroidal galaxies, our own inner Galaxy,

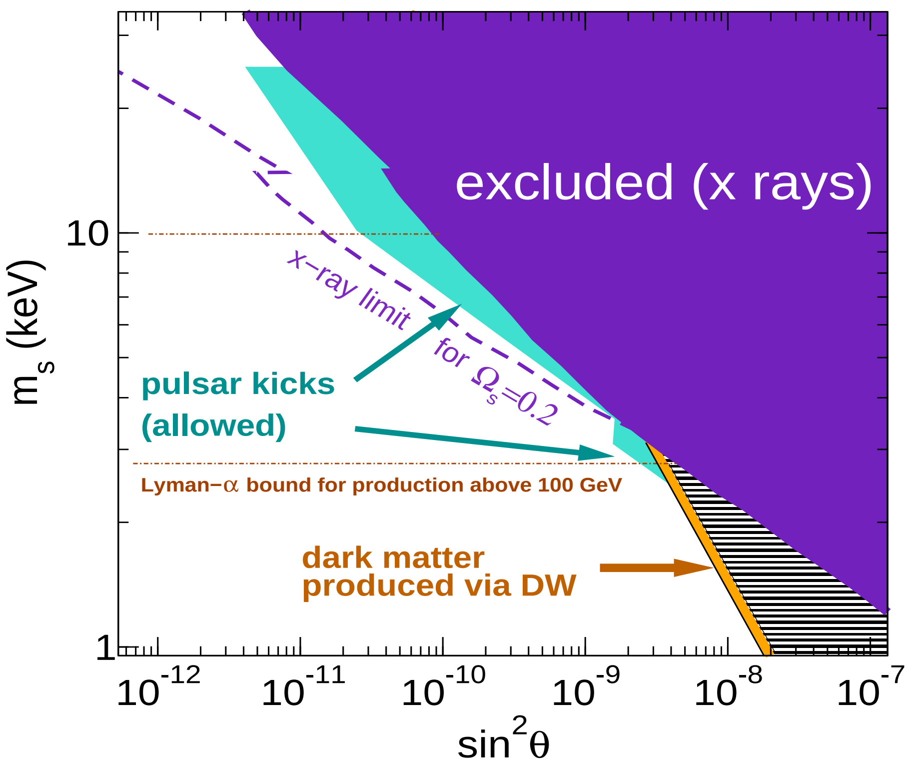

Fig. 4. The X-ray limits reported in ref. [56,66,73] (dashed line) apply if the sterile neutrinos account for all the dark matter ($\Omega_s = 0.2$). The value of Ω_s depends on the production mechanism, but it cannot be lower than the amount produced via the Dodelson Widrow mechanism[18] (except for the lower-reheat scenarios[130]). The model independent exclusion plot (purple region) is obtained by assuming this minimal value. A sterile neutrino with mass 3 keV and $sin^2\theta \approx 3 \times 10^{-9}$, produced at some temperature above 100 GeV, can explain both pulsar kicks and dark matter. This graph was taken from ref.[131] under the permission of the author.

nearby massive galaxies like M31, the next clusters of galaxies like the Virgo cluster, and other clusters further away, all should show a sharp X-ray emission line.[55–57,62,66,72] Fig.1 shows the lifetime of the sterile neutrino for different photon energies. The universal X-ray background should show such a sharp emission line as a wedge, integrating to high redshift. With major effort this line or wedge should be detectable with the current Japanese, American or European X-ray satellites: Large field high spectral resolution spectroscopy is required. Sterile neutrino mass limits are shown in Fig. 4.

5. Outlook

The potential of these right handed neutrinos is impressive, but in all cases we have argued, there is a way out, in each case there is an alternative way to interpret the data set. E.g., for the pulsar kick with the help of neutrinos strong magnetic fields are required, but the MHD simulations suggest that perhaps magnetic fields can do it by themselves, even without the weakly interacting neutrinos.[78–82] The dwarf spheroidal galaxies can in some models be explained without any dark matter at all.[122,123] The early growth of black holes can also be fuelled by other black holes, as long as there are enough in number and their orbital angular momentum can be removed. So many alternatives may replace the sterile neutrino concept.

However, the right handed, sterile neutrinos weakly interacting with the normal left handed neutrinos provide a unifying simple hypothesis, which offers a unique explanation of a large number of phenomena, so by Occam's razor, it seems quite convincing at present.[131] So, given what sterile neutrinos may effect, we may have to call them Weakly Interacting Neutrinos, or soon WINs.

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